

INFRARED SPECTROSCOPY OF STAR FORMATION IN GALAXIES

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ABSTRACT

We have observed the Brackett α ($4.05 \mu\text{m}$) and Brackett γ ($2.17 \mu\text{m}$) lines with $7.2''$ angular and 350 km s^{-1} velocity resolution in 11 infrared-bright galaxies. From these measurements we derive extinctions, Lyman continuum fluxes, and luminosities due to OB stars. The galaxies observed to date are NGC 3690, M83, NGC 5195, Arp 220, NGC 520, NGC 660, NGC 1614, NGC 3079, NGC 6946, NGC 7714, and Maffei 2, all of which have been suggested at some time to be "starburst" objects. The contributions of OB stars to the luminosities of these galaxies can be quantified from our measurements and range from insignificant (Arp 220, NGC 3079, NGC 5195) to sufficient to account for the total energy output (M83, NGC 1614). The OB stellar luminosities observed are as high as $10^{12} L_{\odot}$ in the galaxy NGC 1614. It is noteworthy that star formation can play very different roles in the infrared energy output of galaxies of similar luminosity, as for example Arp 220 and NGC 1614. In addition to probing the star formation process in these galaxies, the Brackett line measurements, when compared to radio and infrared continuum results, have revealed some unexpected and at present imperfectly understood phenomena: 1) in some very luminous sources the radio continuum appears to be suppressed relative to the infrared recombination lines; 2) in many galaxies there is a substantial excess of $10\mu\text{m}$ flux over that predicted from simple models of Lyman α heating of dust if young stars are the only significant energy source.

OBSERVATIONS AND METHODOLOGY

Young O and B stars are likely energy sources for the intense infrared emission observed in many galaxies (Telesco and Harper 1980; Rieke *et al.* 1980; Scoville *et al.* 1983), but non-stellar sources may also be involved (Rieke 1976; Wynn-Williams and Becklin 1985). The first priority in studying star formation in galaxies is to quantify the contribution of young stars to the total luminosity. For this purpose, we have observed the Brackett α ($4.05 \mu\text{m}$) and γ ($2.17 \mu\text{m}$) lines of hydrogen. From the Brackett line strengths one can derive the extinction, the flux of ultraviolet photons, and, with the assumption of an initial mass function, the total number of OB stars present. The properties of this deduced stellar population, including total luminosity, $10 \mu\text{m}$ luminosity, and thermal radio flux, are then compared to the observed values. Details of the method are found in Beck *et al.* (1986), and Turner *et al.* (1986). Uncertainties in the derived quantities depend on their sensitivity to the assumed values of electron temperature, which can affect both the total ionizing flux and extinction derived by 10 to 15 percent; dust temperature, which can change the predicted $10 \mu\text{m}$ flux by up to 50 percent; and the initial mass function, the largest uncertainty, which can change the total luminosity due to young stars by up to a factor of two.

The observations were made using the Cornell Cooled Grating Spectrometer (Beckwith *et al.* 1983) on the NASA Infrared Telescope Facility on Mauna Kea in March and October 1985. All of the galaxies observed are bright, have companions, and have been suggested to contain regions of rapid star formation, but the sample spans a range in morphology, luminosity, distance, and strength of tidal interactions with the companion.

RESULTS

The OB luminosities derived from the Brackett lines indicate that star formation contributes varying amounts to the total infrared luminosities in the galaxy sample. In the three galaxies NGC 5195, Arp 220, and NGC 3079, the OB stellar population was found to contribute only insignificantly (less than 20 percent of the total) to the far-infrared luminosity. Corrections between the small-beam Brackett observations and the large beams of far-infrared measurements used to find the total luminosity cannot explain these discrepancies. By contrast, in NGC 1614 and M83 the luminosity due to OB stars derived from a Miller and Scalo (1979) initial mass function with upper mass limit $30 M_{\odot}$ is actually somewhat greater than the total observed luminosity, indicating that star formation is the primary energy source and that the initial mass function may be truncated. In NGC 6946, NGC 7714, Maffei 2, NGC 660, NGC 520, and NGC 3690 the luminosity of young OB stars is a significant portion of the total observed. When beam size corrections are considered, the observations of these galaxies suggest that star formation is their major luminosity source, although proof will require continuum measurements with higher angular resolution.

From the Brackett line flux, the UV flux and hence the thermal radio continuum flux can be derived. In almost all cases, the predicted thermal radio flux $S_{\text{radio}}^{\text{pr}} < 0.1 - 0.2 S_{\text{radio}}^{\text{tot}}$, with the excess radio emission due to synchrotron emission. There are two possible exceptions in the galaxy sample. The predicted thermal flux from NGC 1614 is about half the total observed. In the most unusual source, M83, $S_{\text{radio}}^{\text{pr}} \sim 70\text{--}100$ mJy whereas $S_{\text{radio}}^{\text{tot}} \sim 30$ mJy. The deficiency in radio emission in M83 could result from a very low electron temperature in the ionized gas ($< 5 \times 10^3$ K) or from optically thick radio continuum emission. The latter possibility is intrinsically more interesting in that it suggests the presence of $> 10^3$ compact HII regions with possibly $10^7 M_{\odot}$ tied up in young stars. We suggest that the burst of star formation in M83 has been short, $< 10^4$ yrs, and that the prodigious rate of star formation cannot be sustained (Turner *et al.* 1986).

The $10\mu\text{m}$ flux can also be derived from the Brackett line fluxes, assuming that dust heating is due solely to Lyman α radiation within HII regions. Small beam ($< 8''$) $10\mu\text{m}$ ground observations when compared to IRAS $10\mu\text{m}$ observations with a larger beam ($0.8' \times 5.0'$), indicate an excellent correlation with on average more than 50% of the $10\mu\text{m}$ emission coming from the nuclear regions. Yet the $10\mu\text{m}$ fluxes predicted from Brackett lines consistently underestimate the observed $10\mu\text{m}$ flux (measured with similar telescope beams) by an average factor of 5. This excess in $10\mu\text{m}$ emission suggests that the nominal ratio of $10\mu\text{m}$ flux to the ionizing flux as derived from Galactic HII regions may not be applicable to external galaxies, especially in the nuclear regions. The $10\mu\text{m}$ excess could be due to unusual distributions of stars and gas, small dust grains, or possibly to higher temperatures in regions with a high spatial density of hot young stars.

THE NATURE OF STAR FORMATION IN GALAXIES

The galaxies in this sample for which OB stars are the primary energy source cover a wide range of luminosities, morphologies, and interaction histories. The Brackett line observations suggest that the infrared luminosity, radio continuum flux, and $10\mu\text{m}$ emission may not be practical quantitative predictors of star formation activity under these circumstances. In some of the galaxies observed the thermal radio flux is lower than that predicted from the Brackett lines; in all of the galaxies the $10\mu\text{m}$ flux is significantly higher than the OB stars can account for if the emitting region behaves as do "normal" Galactic HII regions. These results imply that it is very difficult to unambiguously predict the spectral signature of star formation. Complicating factors as optically thick HII regions or non-equilibrium heating of small grains may have to be considered in models of such objects. This sample of bright infrared galaxies appears to be a disparate group and difficult to model. This may be only what should be expected from galaxies known to be undergoing a shortlived, unusual, and highly energetic stage of development.

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DISCUSSION

PUGET:

If your $10\mu\text{m}$ excess is due to small grains, the observations in our Galaxy show that the excess is much larger in the neutral medium than in HII regions, so the $10\mu\text{m}$ excess may be a handle on the relative distribution of O stars and B stars.

HO:

That is certainly a good suggestion. When more detailed mapping is available, we can compare the $10\mu\text{m}$ excess and the ionizing flux in terms of spatial distribution.

GALLAGHER:

What is the evidence for an outflow from the nucleus of NGC 3079?

HO:

Hummel and collaborators have published a radio continuum map which shows an extension perpendicular to the plane of the galaxy.

YOUNG:

In your comparison of $10\mu\text{m}$ fluxes in a $7''$ aperture, what was the source of IR data? The Point Source Catalog will underestimate the total flux in many of the galaxies which are extended, and the coadded survey fluxes are higher than those in the Extragalactic Catalog.

HO:

For examining the $10\mu\text{m}$ excess, we used the Brackett lines to predict a $10\mu\text{m}$ flux in a $7''$ beam. We compared this flux to $10\mu\text{m}$ flux actually observed in ground-based observations with angular resolution $\leq 8''$. To determine the dominance of nuclear $10\mu\text{m}$ emission, we compare the ground-based photometry with IRAS $12\mu\text{m}$ flux from the Extragalactic Catalog. We don't think extended emission (with respect to the IRAS beam) is likely for our sample, because these sources have high correlation coefficients, $\sim 99\%$, consistent with 'point-like' (with respect to IRAS beam) distributions.

TELESCO:

All the $12\mu\text{m}$ IRAS flux in M83 can be accounted for in a recent map at $10.8\mu\text{m}$ (Telesco *et al*; this conference). Nearly all falls within the central $20''$ diameter region. However, most of this is not in the central $7''$. The infrared source is compact, but not **extremely** compact.

HO:

In our comparison of $10\mu\text{m}$ and Brackett flux for M83, we have actually summed over the positions mapped in the Brackett line. We have been careful to compare data that are at the same positions and with similar beams. M83 was the strongest source in our sample so that a little mapping was possible.